MIXED MODE TESTING OF ADHESIVE LAYER

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ABSTRACT

For a flexible linear elastic adhesive, the mode mixity of a single-layer adhesive joint is directly related to the deformation of the adhesive layer at the crack tip. The governing equations for linear elastic single-layer adhesive joints show that the mode mixity depends on the external loads, the properties of the adherends and often on the flexibility of the adhesive layer. This implies some fundamental problems that have to be addressed before an experimental method can be established. Requirements for the design of a specimen configuration for mixed mode testing of adhesive layer are given. A new specimen configuration is proposed and some preliminary experimental results are given.

Keywords: adhesive layer; mixed mode testing; energy release rate; inverse method

1. INTRODUCTION

For bonding purposes, the adhesive is applied and constrained between two bodies; the adhesive becomes a layer which is usually much thinner than the bonded bodies. A thin adhesive layer behaves differently compared to the adhesive as a bulk material. In practice, adhesive joints are likely to be loaded in a combination of peel and shear, which causes a mixed mode loading of the adhesive layer. Generally, the loading can be viewed as a combination of three modes: peel (mode I) and two shear modes (II and III). The behaviour in the two shear modes is similar.

Experiments show that the fracture energy of adhesive joints loaded in shear, $J_{II}$ or $J_{III}$, is much larger than the fracture energy in peel, $J_{IC}$ (Andersson and Stigh 2004; Chai 2003; Leffler et al 2006). Moreover, it appears much more difficult to measure the properties in mixed mode loading. To this end, a number of different specimens and techniques have been developed. Different methods for separating the mode mixity of the adhesive joint into peel (mode I) and shear (mode II) components have also been developed.
Under quasi-static loading, the mechanical behaviour of adhesive joints mainly depends on the material and geometrical properties of the joints, as well as the loading system. Unbalances in the loading system and/or unbalances in the adherends in terms of geometrical and/or material properties are the causes to the existence of the mode mixity in an adhesive layer.

For a symmetric adhesive joint, i.e. a joint with identical adherends, the mode mixity is solely due to the loading system. In this case, the loading system can always be considered as an assembly of a symmetric part and an anti-symmetric part. For linear elastic joints, in which case superposition is allowed, the mode I loading is given by the symmetric part while the mode II loading is given by the anti-symmetric part. For example, Reeder and Crews (1990) suggested the Mixed Mode Bending (MMB) specimen for achieving a range of mode mixities on an adhesive joint. The symmetric joint is loaded in a combination of the loading of a Double Cantilever Beam (DCB) specimen and an End Notched Flexure (ENF) specimen. The mode mixity of the MMB-specimen is adjusted by applying the external force $P$ with varied lever length. For evaluation of the energy release rate (ERR), simple beam theory is applied and the adhesive layer is neglected. The ERR is decomposed according to the external load; the ERR in mode I is directly related to the peel force in DCB and the ERR in mode II is directly related to the shear force in ENF.

The mode mixity can also be achieved by introducing geometrical or material unbalances into a load-balanced joint, e.g. a DCB-specimen or a Crack Lap Shear (CLS) specimen. However, none of the proposed methods: the unsymmetrical DCB or CLS-specimen, or the MMB-specimen, can achieve mode mixity in the complete spectrum, i.e. from pure mode I to pure mode II (Högberg 2004).

In this paper, a so called the Mixed-mode Cantilever Beam (MCB) specimen is designed and used for mixed mode testing of adhesive layer. Inverse method for evaluation of the experiment and the requirements for the design of a specimen configuration are given. Finally, the preliminary test result with the MCB-specimen is given.

2. SPECIMEN DESIGN

In general, to make valuable conclusions from experiments, a number of specimens are required for achieving repeatability and reliability. It is then more suitable to use the same specimen geometry and vary the loading system in order to achieve a range of mode mixities. Thus, only one type of specimen has to be designed and manufactured. This sets design requirements on the loading system:

- **flexibility**: the loading system should be simply adjustable for testing different mode mixities,
- **variety**: the ability for attaining the entire spectrum of mode mixities, i.e. from pure mode I to pure mode II,
- **stability**: the mode mixity should vary steadily and smoothly by a pre-defined adjusting parameter in the loading system.

Based on the geometry of a semi-infinitive symmetric DCB-specimen, by combining the basic loading cases of DCB, ELS and CLS given by Högberg (2004), a testing specimen, referred to as the Mixed mode double Cantilever Beam (MCB) specimen, is designed, cf. Fig. 1.

Each adherend at the free end of the MCB-specimen is loaded with an external force, $F$, with the same magnitude but opposite direction. This pair of forces are self-balancing and their direction of action is defined by the angle $\alpha$. Figure 1 illustrates the loading system on the MCB-
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![Diagram of MCB specimen](image)

**Fig 1 Mixed mode double Cantilever Beam (MCB) specimen as superposition of the basic loading systems.**

The specimen is a superposition of the basic loading systems: DCB for peel loading, ELS and CLS for shear loading. The sectional forces at the crack tip, \( x = 0 \), in Fig. 1 are:

\[
N = F \cos \alpha, \quad V = F \sin \alpha
\]

Superposition of the deformations for the basic loading systems gives the ERR in mode I and mode II as

\[
J_I = \frac{12}{E_1 t_1} \left( \frac{F}{b} \right)^2 \left( \frac{1}{\kappa_p t_1} + \frac{a}{t_1} \right)^2 \sin^2 \alpha
\]

\[
J_{II} = \frac{4}{E_1 t_1} \left( \frac{F}{b} \right)^2 \cos^2 \alpha
\]

where \( E_1 \) and \( t_1 \) is the Young’s modulus and the thickness of the adherends, respectively; \( b \) is the joint width. The wave number \( \kappa_p = (6E)/(tE_1 t_1) \), where \( E \) is the effective peel modulus and \( t \) is the thickness of the adhesive layer, respectively (Högberg 2004). The mode mixity is defined by

\[
\Lambda = \frac{J_{II}}{J_I + J_{II}}
\]

A combination of Eqs. (2) and (3), gives the mode mixity of the MBC-specimen in terms of the force angle \( \alpha \)

\[
\Lambda(\alpha) = \frac{\cos^2 \alpha}{3 \left( \frac{1}{\kappa_p t_1} + \frac{a}{t_1} \right)^2 \sin^2 \alpha + \cos^2 \alpha}
\]

Pure mode I loading is obtained when \( \alpha = 90^\circ \) and pure mode II when \( \alpha = 0^\circ \). As shown in Eq. (4), the crack length \( a \) also affects the mode mixity. A theoretical study shows that the loading system on a MCB-specimen with a short crack length offers exceptional flexibility, variety and stability. The crack length \( a = 0 \) is chosen.
3. INVERSE METHOD

An inverse method is employed to experimentally obtain the constitutive behaviour of adhesive layers in pure mode I and pure mode II (Andersson and Stigh 2004; Leffler et al 2006). This method is based on the energetic balance of a specimen by use of the $J$-integral (Rice 1968). Here, the inverse method is extended to mixed mode loading. For an elastic adhesive joint, linear or nonlinear, the $J$-integral is defined by

$$J = \int_s (W d\gamma - T \cdot \frac{du}{dx} ds)$$  \hspace{1cm} (5)$$

where $W = \int \sigma d\epsilon$ is the strain energy density. The traction vector $T = \sigma n$, where $\sigma$ is the stress tensor and $n$ the unit vector normal and outwards to the counter-clockwise integration path $s$. The deformation vector and the strain tensor are denoted $u$ and $\epsilon$, respectively. For the MCB-specimen, a closed integration path $s$ without singularity is chosen, as shown in Fig. 2. The parts of the path that are not traction-free are situated at the crack tip region, denoted by DA, AB and BC. The $J$-integral along the closed integration path $s$, or path AB and BA, yields energetic force equilibrium

$$J_{AB} + J_{BA} = 0 \quad \Leftrightarrow \quad J_{AB} = -J_{BA}$$  \hspace{1cm} (6a, b)$$

The path AB goes through the adhesive layer at the crack tip. The main deformation modes of the adhesive layer are: peel (mode I), shear (mode II) or mixed mode. Evaluating the terms in Eq. (5) gives

$$J_{AB} = \int_0^r \tau d\bar{\gamma} + \int_0^w \sigma d\bar{\epsilon} = J_{adh}$$  \hspace{1cm} (7)$$

On the path BA, only the paths DA and BC contribute to $J_{BA}$. Assuming the adherends to deform according to linear elastic Euler-Bernoulli beam theory, Eq. (5) yields the $J$-integral through the adherends, or the total ERR due to the load

$$-J_{BA} = \frac{12}{E_1 t_1} \left( \frac{F \sin \alpha}{b} \frac{a}{t_1} \right)^2 + \frac{4}{E_1 t_1} \left( \frac{F \cos \alpha}{b} \right)^2 + \frac{F \sin \alpha}{b} (w'_1 - w'_2) = J_{load}$$  \hspace{1cm} (8)$$

where $w'_{1,2}$ is the rotation of the adherends at the crack tip. All parameters on the right hand side of Eq. (8) are measurable in the experiment, which enables the evaluation of the constitutive behaviour of the adhesive layer in term of stress-deformation relationships by

Fig. 2 Integration path $s$ on the MCB-specimen.
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\[ \sigma(w, v) = \frac{\partial J_{AB}}{\partial w}, \quad \tau(w, v) = \frac{\partial J_{AB}}{\partial v} \]  
\[ (9a, b) \]

This method is referred to as the inverse method to determine the constitutive behaviour of a material through the overall response of the structure. The \( J \)-integral is valid for elastic material and any elastoplastic material under monotonic loading.

4 MCB-SPECIMEN GEOMETRY

The MCB-specimen with \( a = 0 \) satisfies all the requirements set on the loading system. That is, the entire spectrum of mode mixity can be achieved smoothly by one pre-defined adjusting parameter: the loading angle \( \alpha \). However, the theory evaluation of the experiment sets more requirements on the MCB-geometry (Högberg and Stigh 2006).

1. The adhesive layer should be thin and flexible in comparison with the adherends. This sets requirement on the relative stiffness of the adherends as compared to the adhesive as 
\[ \frac{E_1}{E_1} \frac{t}{t_1} > 0.1 \]  
\[ (10) \]

2. The deformation of the adhesive layer at the crack tip is small in comparison to the overall dimensions of the joint.

3. The overlap length should be long since the specimen is considered as semi-infinite.

4. The adherends should deform linear elastically. The maximum bending moment in an adherend occurs near the crack tip and its magnitude is close to the bending moment at the crack tip. Thus, the maximum stress in the adherends at \( x = 0 \) should be smaller than the yield strength of the adherends, \( \sigma_{\text{yield}} \), i.e.
\[ \sigma_{\text{max}} = \frac{F}{bt_1} < \sigma_{\text{yield}} \]  
\[ (11) \]

where \( c = 4\cos \alpha + 6a/t_1 \sin \alpha \).

5. It should be possible to exceed the fracture energy in all mode mixities. By assuming linear elastic behaviour of the adhesive layer and the maximum fracture energy is attained in pure mode II
\[ J_{II} = \frac{4}{E_1 t_1} \left( \frac{F}{b} \right)^2 > J_{\text{fle}} \]  
\[ (12) \]

which gives a conservative criterion on the minimum force.

The material choice is the same as for the mode I experiment performed with the DCB-specimen (Andersson and Stigh 2004) and the mode II experiment performed with the ENF-specimen (Leffler et al 2006). The adhesive, DOW Betamate XW1044-3, is a toughened epoxy, with \( E = 2 \) GPa and \( v = 0.4 \). The adherends are made of tool steel, with \( E_1 = 200 \) GPa, \( v = 0.3 \) and \( \sigma_{\text{yield}} = 500 \) MPa. With these chosen materials, the following dimension of the MCB-specimen satisfies all requirements given above

Overall joint: \( L = 100 \) mm, \( b = 4 \) mm, \( a = 0 \) mm
Adhesive: \( t = 0.2 \) mm
Adherends: \( t_1 = 10 \) mm
These dimensions are optimized for minimum weight of the specimen and minimum force. The overlapped part of the specimen weights less than 0.05 kg and the maximum external force required is less than 4 kN.

5. EXPERIMENT

The specimens are fabricated by bonding two 10 mm thick steel plates with 0.2 mm thick adhesive. Teflon film stripes in 0.2 mm are inserted between the plates to ensure the consistency of the thickness of the adhesive layer, as well as the crack tip position. After curing at 180°C for 30 min, the joined plates are left in oven to gradually return to room temperature to minimise residual stresses. The joined plates are then cut into 4 mm wide specimens. For later optical measurement, speckle pattern is applied with black and white spray paint.

Two fixtures, cf. Fig. 3, are designed to allow the specimen to be loaded with an uniaxial tensile machine. Seven different mode mixities can be achieved, with loading angle $\alpha = 0, 15, 30, 45, 60, 75$ and 90°. Two forks are also manufactured to allow the tensile machine to grip the fixtures.
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at different angles.

The loading rate is kept constant at 5 µm/s and the loading force is recorded. The commercial optical measuring system, ARAMIS with 4 Mpixel cameras, is used for measuring the displacement of the MCB-specimen under the loading process. Resolution of 0.67 µm/pixel is achieved and an area with approximately 35 mm long adhesive layer is captured. Thus, the necessary deformation parameters for evaluating the $J$-integral in Eqs. (8) and (9) can be obtained.

Totally 12 specimens are tested, 5 of them are measured with ARAMIS system. For the tested mode mixities, the adhesive layer tends to deform first in shear; peel deformation takes over towards the end of the fracture process, cf. Fig. 4. For both $\alpha = 90$ and $0^\circ$, i.e. the expected pure mode I and II cases, mixed mode deformation is observed. The maximum loading force lies between 820 N to 3240 N from mode I to mode II. The ERR is then evaluated by Eq. (8). The fracture energy lies between 0.88 N/mm to 1.2 N/mm from mode I to II, cf. Fig. 5. For loading cases $\alpha = 90$, 75 and 45°, $J_I$ dominates; for $\alpha = 15^\circ$, $J_I$ and $J_{II}$ are at the same level. The adhesive layer is stronger when shear mode increases.

The fracture surfaces are examinated under microscope; photos are taken and shown in Fig. 6. Interfacial fracture occurs at crack tip region for $\alpha = 0$ and $15^\circ$; elsewhere cohesive fracture occurs. Hardly any air bubbles or other flaws are observed on the fracture surfaces. Adhesive layer starts at the desired position. Thus, the manufacturing process of the specimens is successful.

![Fig. 5. The evaluated ERR, $J_I$, $J_{II}$ and the total $J$.](image)

![Fig. 6. Fracture surfaces.](image)
6. CONCLUSION

For mixed mode testing of adhesive layer, design requirements are set with consideration to desired loading modes, evaluation methods, as well as manufacturing and experimental possibilities. The Mixed-mode Cantilever Beam (MCB) specimen is designed to fulfil these requirements. This testing method uses inverse method to obtain mixed mode behaviour of an adhesive layer loaded in seven combinations of mode mixities from mode I to mode II. The preliminary test result shows that the adhesive layer is stronger in shear dominating modes, which is expected. The deformation path is nonlinear. More experiments will be conducted to obtain repeatability in measuring results. By then, more reliable conclusions can be drawn.

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